UNIVERSITY OF TECHNOLOGY, SYDNEY

Efficient Algorithms and a Two-Stage Framework for Autonomous Exploration of Complex 3D Environments Using a Climbing Robot

by

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I, Phillip Quin , declare that this thesis titled, 'Efficient Algorithms and a Two-Stage Framework for Autonomous Exploration of Complex 3D Environments Using a Climbing Robot' and the work presented in it are my own. I confirm that:

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- Where I have consulted the published work of others, this is always clearly attributed.
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- I have acknowledged all main sources of help.
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Abstract

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Enabling robots to autonomously explore complex 3D environments is crucial in facilitating the automation of many real-world tasks. There exist many algorithms for exploring unknown environments with autonomous robots. Most of these are restricted to the 2D case, or to cases where the robot can be abstracted as a holonomic point robot. Algorithms that deal with the 3D case restrict the robot's possible positions to the 2D plane, or assume that the robot can freely move through any empty space, like an idealised quadrocopter.

This thesis presents a two-stage exploration framework that allows robots to consider any adherable surface in a 3D environment as a potential position from which to conduct exploration. The framework is therefore suitable to any robotic platform that must at all times maintain contact with a surface, but where this surface need not be the floor plane.

A Nearest Neighbours Exploration Approach (NNEA) is developed to accomplish exploration of the environment immediately surrounding the robot when the robot is fixed to a position on a surface. In this approach, the Next Best Viewpoint is selected first by evaluating and choosing between candidate viewpoints that are within a bounded range of the robot's current position. NNEA is demonstrated in experiments in a real bridge environment for the case of a high degrees of freedom (DOF) robot arm with a fixed base. NNEA is shown to result in faster exploration times in the case of a high-DOF robot arm in a fixed base position.

Four frontier detection algorithms are proposed and investigated for determining the set of frontiers—the boundary between known and unknown space—after each map update. The resulting frontiers are used to limit which candidate positions need to be considered for exploration. The novel frontier detection algorithms are compared to other state of the art algorithms and are found to be suited for efficient frontier detection in different situations.

A novel graph-based method for selecting the Next Best Base location (NBB) is presented in which the map is used to create an updated graph of possible positions for the robot base, sampled from all surfaces. Positions that are sufficiently close to the frontiers are selected as candidate positions for the robot to move to next. The information that could be gained from each reachable candidate position is estimated. A cost function determines which candidate is the best to move to next, and the robot moves to that position to take

another sequence of scans. This method is demonstrated in simulations and experiments to be efficient in minimising the computation required to select and move to the NBB.

The exploration framework and the developed algorithms and approach are demonstrated in simulation in an environment made up of unconnected surfaces, large enough that the robot is required to repeatedly move through the environment in order to fully explore it. The framework is shown to result in efficient exploration of the observable environment.

Acknowledgements

If you want to build a ship, don't drum up people together to collect wood and don't assign them tasks and work, but rather teach them to long for the endless immensity of the sea.

— Antoine de Saint-Exupéry

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Abbreviations

2D	2 Dimensional
3D	3 Dimensional
AXBAM	Autonomous eXploration to Build A Map, system
BFS	Breadth-First Search
C-space	Configuration Space of manipulator
CBFD	Change-Based Frontier Detection
DFS	Depth-First Search
DOF	Degrees of Freedom
EWFD	Expanding Wavefront Frontier Detection
FFD	Fast Frontier Detection
FOV	Field Of View
FTFD	Frontier-Tracing Frontier Detection
NBB	Next Best Base location
NBV	Next Best Viewpoint
NN	Nearest Neighour
NNEA	Nearest Neighour Exploration Approach
NNEA-B	Nearest Neighour Exploration Approach with Backtracking
RGB-D	Red Green Blue Depth camera.
RRT	Rapidly-exploring Random Trees
SBFD	State-Based Frontier Detection
SLAM	Simultaneous Localisation And Mapping
WFD	Wavefront Frontier Detection
WFD-INC	Incremental Wavefront Frontier Detection

Nomenclature

	General Formatting Style
$f(\cdots)$	A scalar valued function
$\mathbf{f}(\cdots)$	A vector valued function
$[\cdots]^T$	Transpose
$\lvert\cdot\rvert$	Absolute value
$\lVert\cdot\rVert$	Vector length and normalised vector
$A \setminus B$	The set A without any elements that are also in B. Equivalent to $B^c \cap A$.
$\mathbb{N}^0$	Natural numbers greater or equal to zero; e.g. 0, 1, 2, 3, ...
$O(g(x))$	Big O notation. $f(x) = O(g(x))$ means $f(x)$ is bounded above asymptotically by $g(x)$. I.e. $\lvert f(x)\rvert \leq k \times \lvert g(x)\rvert$, for sufficiently large x, and some positive k.
$\Omega(g(x))$	Big Omega notation. $f(x) = \Omega(g(x))$ means $f(x)$ is bounded below asymptotically by $g(x)$. I.e. $\lvert f(x)\rvert \geq k \times \lvert g(x)\rvert$, for sufficiently large x, and some positive k.
$\mathbb{R}^2$	The set of points in 2D Euclidean space; e.g. (1.2, -57.5).
$\mathbb{R}^3$	The set of points in 3D Euclidean space; e.g. (-3.4, 105.19, 8).
$\Theta(g(x))$	Big Theta notation. $f(x) = \Omega(g(x))$ means $f(x)$ is bounded asymptotically above and below by $g(x)$. I.e. $k_1 \times \lvert g(x)\rvert \leq \lvert f(x)\rvert \leq k_2 \times \lvert g(x)\rvert$, for sufficiently large x, and some positive k_1 and k_2.
	Nearest Neighbour Exploration Approach
$\mathcal{A}$	The robot.

$\mathcal{A}(\mathbf{q})$	The space taken up by the robot in configuration $\mathbf{q}$.
$\mathcal{C}$	Configuration space.
$\Delta\theta$	The angle used to determine neighbouring configurations.
$\mathcal{H}(\mathbf{q})$	The information value of a configuration $\mathbf{q}$.
$\mathcal{P}^t_{free}$	The set of known free-space at time t.
$\mathcal{P}^t_{obs}$	The set of known obstacles at time t.
$\mathcal{P}^t_{unk}$	The set of unknown space at time t.
Q_a	The set of candidate configurations under consideration by AXBAM.
Q^t_n	The set of candidate configurations under consideration by NNEA at time t.
$\mathbf{q}$	A robot configuration, representing a vector of joint angles.
$\mathbf{q}^t_{curr}$	The robot configuration at time t.
$\mathbf{q}^t_{nbv}$	The next best view configuration at time t.
t	A variable representing time.
${}^oT^{\mathbf{q}}_s$	The transform from map origin to sensor origin based on the robot configuration $\mathbf{q}$.
τ_a	The information threshold under which configurations will be discarded in the AXBAM algorithm.
τ_n	The information threshold under which configurations will be discarded in the Nearest Neighbours phase of NNEA.
	Frontier Detection Algorithms
A_t	The active area of the observation at time t.
A_{max}	The largest size of any possible active area.
$\mathcal{E}_{max}$	The largest size that any set of cells forming the boundary of any $\mathcal{S}(O_t)$ could be.
$\mathcal{E}(O_t)$	The set of cells in $\mathcal{S}(O_t)$ that are on the edge of the map or adjacent to cells not in $\mathcal{S}(O_t)$.
$\mathcal{F}_{aa}$	The set of known frontiers inside the active area under consideration.
$\mathcal{F}_{new}$	The set of known frontiers that, when added to the set F_{t-1}, will make it become F_t.

$\mathcal{F}_t$	The set of known frontiers at time t.
$\mathcal{F}_{t-1}$	The set of known frontiers at time $t-1$.
M	The set of cells in the map.
M_{free}	The set of free-space cells in the map.
O_t	The sensor observation made at time t.
o_t	The number of individual observations made as part of O_t.
$\mathcal{S}_{max}$	The largest size that any set of cells covered by the sensor could be.
$\mathcal{S}(O_t)$	The set of cells covered by the observation O_t.

Selecting the Next Best Base Location

A	The set of valid attachment positions.
$\mathcal{C}$	The set of candidate attachment positions.
$C(a, a_0)$	The cost of reaching attachment position a given the robot begins at a_0.
d_{max}	The maximum transition step the robot can make across a surface.
d_{min}	The minimum transition step the robot can make across a surface.
$e_{i,j}$	An edge linking attachment position i and j.
$\mathcal{F}$	The set of frontiers.
$H(a)$	A function returning the estimated information value of an attachment position a.
$\mathcal{M}_o$	The map of free and occupied space.
$\mathcal{M}_s$	The map of known surfaces.
$\mathbf{p}_{i,j,k}$	A robot trajectory assuming the robot starts with the end effector at to attachment position i, the base affixed to attachment position j, and the end effector will be moved to attachment position k.
$\mathbf{q}_{j,k}$	A robot configuration "straddling" the base positions j and k.
r_l	The length of the robot.
r_s	The trustworthy range of the sensor.
$s()$	The sampling policy which takes as argument a map of surfaces.
${}^0T_b$	The homogeneous transform describing the robot base.

τ_s	The threshold under which an attachment position is considered unsafe.
$U(g, s)$	The utility function taking as arguments a goal node g and start node s.
V_r	A sphere of radius r.

Glossary of Terms

Autonomous	Without human intervention.
Base	The footpad of the robot that is currently affixed to the surface.
Binary Tree	A tree data structure in which each node has at most two children.
Bounding Box	The smallest box, usually axis-aligned, that can be made to contain a set of given points.
Candidate	A node/position considered as the next potential position from which the robot should make new observation(s) of the environment.
Cell	A particular area of space in a discretised 2D map, usually indicated by an x and y index pair or coordinate. The same as a cell in a spreadsheet.
Climbing Robot	A robot designed to be able to travel along vertical surfaces in some fashion.
Configuration-space	A mathematically abstract space whose dimensions are the parameters available for change by the robot. For example, a robot that has 2 joints would have a configuration space that is 2D. The axes of the space are the permissible values of that parameter.
End Effector	The device at the end of a robot manipulator which with the robot interacts with the environment.
Environment	The area or volume of space that the robot will operate in.
Ferromagnetic	Made of metals to which magnets are attracted.
Footpad	A link on the end of the robot that affixes itself to the surface.

Freespace	Space that is known to be empty of obstacles.
Frontier	The boundary between known free-space and unknown space.
Greedy	An algorithm in computing is considered greedy if it makes decisions based on short time-horizons, including as little as a single time-step.
Holonomic	An object (in the context of this thesis, a robot) is holonomic if its kinematic properties would allow it to freely move in any direction from a given position.
Information	A measure of uncertainty in the state of an environment/model.
Joint Effort	The sum of the difference in joint angles between two or more poses.
K-d Tree	A tree for storing points in k-dimensional space.
Kinematic Chain	A configuration of rigid bodies connected by joints.
Kinematics	The description of the motion of a system of objects.
Known Space	Space that is either known to be empty of obstacles, or known to contain an obstacle.
Manipulator Robot	A series of motors connected by joints, usually with one end fixed in place and the other end affixed with a tool or gripper.
Map	A representation of the environment, typically updated, maintained and used by the robot.
Occupancy Map	A discretised grid representation of the environment, made up of cells that store values representing the probability that that position in space contains an obstacle.
Octree	A compact method for storing a 3D occupancy map. The grid is stored as a tree so that when all eight children of a parent node have the same value, they can be deleted and the parent holds the value instead.
Obstacle	An impassable object.
Operator	A person in charge of controlling or monitoring a robot as it performs a task.
Point Robot	A robot that can be abstracted as a point in space.

Pose	The position and configuration of an object such as a robot, robot joint, end effector or sensor.
Quadtree	A compact method for storing a 2D occupancy map. The grid is stored as a tree so that when all four children of a parent node have the same value, they can be deleted and the parent holds the value instead.
Ray-cast/Ray-trace	Techniques for calculating the path of a ray through a grid or set of objects to determine which it interacts with.
Robot	A machine able to perform actions based on information it collects about the environment around it.
Surface Map	A map of 3D surface information.
Teleoperation	Operation of a machine from a distance by a human operator.
Triangle Mesh	A method for representing surfaces as a set of triangles connected by their edges and vertices.
Tether	A cable connecting the robot to either a control station, a power source, or a larger structure for safety, or a combination of these.
Unknown Space	Space that whose obstacle status is not known. It might or might not contain an obstacle.
Viewpoint	The position and orientation of a sensor in space, often as a result of a particular robot configuration, which determine what portion of the environment is covered by the sensor field of view.
Voxel	A particular volume of space in a 3D discretised map, usually represented by an (x,y,z) coordinate.